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THE STUDY AND ANALYSIS OF STRESS DISTRIBUTION SUBJECTED ON THE REPLACEMENT KNEE JOINT COMPONENTS USING PHOTO-ELASTICITY AND NUMERICAL METHODS

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ABSTRACT

The failure of a knee joint can cause serious health problems and usually leads to the replacement of the joint surgically. The distribution of stresses in the region of the joint shall be computed and analysed via photo-elasticity method and numerically with the use of ANSYS workbench. Numerical stresses will be measured and estimated for ground, air sneakers and ground air sneakers with silicon damped cases and compared with the case of without using damped sneakers. The patient is of age 56 years, weight 85 kg, height 165 cm and leg length of 98 cm. The contours of the distributed stresses via the use of both the numerical and photo-elasticity methods showed that the sneakers with ground, air with silicon damping had minimum stress values (34.71 F& 43,99) MPa for the numerical and photo-elasticity methods respectively. Also, both methods predicted that damped sneakers were safe to use while the maximum safety factor was recorded when using ground, air sneakers with a value of 30.98 and 30.58 for femoral component, while for tibia component with a value of 17.61 and 18.27, while for articulating surface with a value of 8.63 and 15.94for numerical and photo-elasticity methods respectively.

KEYWORDS: Total Knee Replacement, Photo-Elasticity, ANSYS, Damping Shoes & Safety Factor

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Original Article

INTRODUCTION

Arthoplasty is a surgical procedure to relieve pain and disability in the knee joint usually by knee replacement. It is commonly used to treat patients that suffer from osteoarthritis, [1] as well as other knee diseases such as rheumatoid arthritis, psoriatic arthritis and patients with severe deformity from advanced rheumatoid arthritis, trauma, or long-standing osteoarthritis. It is common among the elderly to suffer intolerable pain as a result of osteoarthritis other major causes include e meniscus tears, cartilage defects, and ligament tears. The operations that are performed for treatment are usually complicated. Arthoplasty are of two types either partial or total knee replacement [2]. Surface knee joints which are damaged, injured or infected are replaced by metal or plastic components shaped similar to the part which is being replaced to permit the continuation of the movement of the knee, [3] as shown in Figure 1, [3].

The Photo-elastic method is used to analyse stresses experimentally by taking advantage of the birefringence effect that appear on the experimented [4] materials. The very name of this method reflects its nature, where it makes use of the light rays by optical methods. Elasticity not only does it depict the study of deformation and stresses in elastic bodies [5], but is also able to present solutions to two and three dimensional problems..

Figure 1: Total Knee Replacement, [3].

General Equations

The forces for the lower limb joint were assessed by theoretical equations by the use of kinematics and kinetic equations of motion. The 2-D sagittal plane linkage was modelled after a human lower limb which comprised of two rigid segments, segments and analysed using the principles of the kinematics and kinetics, by modelling the lower limb (ankle, shank) as a segment. These forces were applied to the segment to measure the distribution stress by using ANSYS work bench (V.16) and photo elasticity. By applying the general equation of motion on each segment [6-7],

$$+\rightarrow \sum f_x = m.\, a_{xc} \tag{1}$$

$$+\uparrow \sum f_y = m.\, a_{yc} \tag{2}$$

For ankle and by applying the above equations of motion on the free body diagram forces of ankle segment as shown in Figure. 2, the resultant ankle forces can be calculated as follows [6-7],

$$F_{Xankle} = m_{foot}.\, a_{xfoot} + G_X \tag{3}$$

$$F_{Yankle} = m_{foot}.\, a_{yfoot} + m_{foot}.\, g + G_Y \tag{4}$$

Also, for the shank segment shown in Figure (3), the resultant force are [6-7]:

$$F_{Xknee} = m_{shank}.\, a_{xshank} + F_{Xankle} \tag{5}$$

$$F_{Yknee} = m_{shank}.\, a_{yshank} + m_{shank}.\, g + F_{Yankle} \tag{6}$$

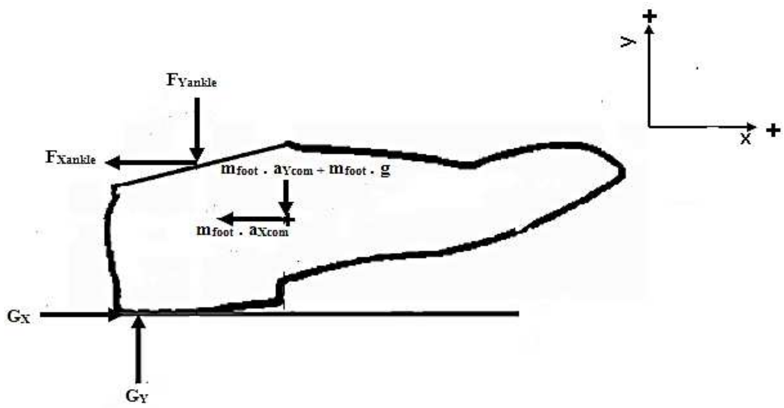


Figure 2: Free Body Diagram of the Foot Segment [6, 7]

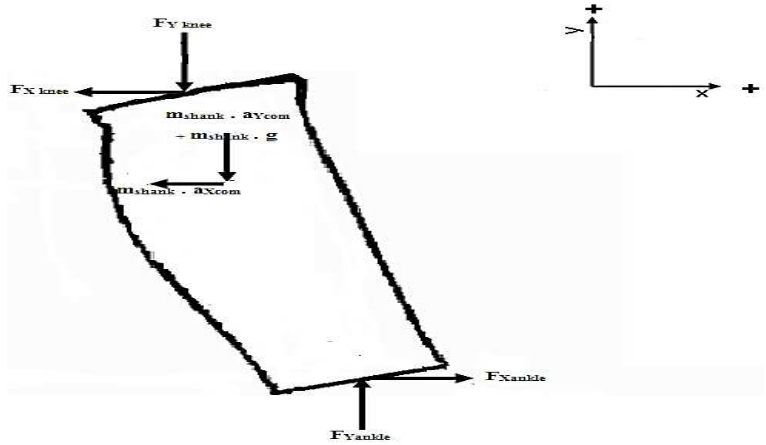


Figure 3: Free Body Diagram of the Shank Segment [6, 7]

EXPERIMENTAL WORK

Multi steps were taken in order to determine the distributed stress for the used structure [8-15], this was performed with the aid of the photo-elastic method.

The 1st step is to make a model for the materials to be used, the material properties are evaluated. Lastly the distributed stresses for the knee is evaluated by implementing the photo-elastic method. Due to the experimental results being acceptable, [16-20], therefore we can depend on the experimental results for the mechanical properties which were obtained experimentally, [21-29].

Material of Test Models

Choosing the right material for the model that will undergo photo-elastic stress analysis is an important factor. An ideal material achieves the following properties Transparency birefringence, Sensitivity to either stress or strain, Linear characteristics, Mechanical and optical isotropy and homogeneity, Machinability, and Free of residual stresses, [30].

The models that were tested in the experimental work were manufactured from a photo-elastic material sheet which had the dimensions (60 cm x 30 cm and a thickness (T) of (1 cm). The polycarbonate material properties are in Table 1.

Table 1: Mechanical Properties of Polycarbonate Material [31]

Properties	Values in SI Unit	
Density	1.20 *10³	kg/m³
Modulus of elasticity	2.3	GPa
Tensile strength	68	MPa
Elongation	130	_____
Poisson ratio	0.35	%
Stress-optical constant	7	N/mm/fringe

Material Properties

The mechanical properties can be evaluated from experimental parts, [32-33]. Therefore, Table 2 shows the properties of the material that was used in this study of the knee prosthesis. Titanium alloys are usually used for replacing knee joints and its parts i.e femoral and tibia, whereas polyethylene is used for articulating surfaces.

Table 2: Material Properties of Total Knee Replacement

Replacement Knee Joint Parts	Material	Young's Modulus (MPa)	Poisson Ratio (v)	Density g/cm^3	Yield Strength (MPa)
Femoral component	titanium alloy	96000	0.36	4.62	930
Tibia component	titanium alloy	96000	0.36	4.62	930
Articulating surface	polyethylene	1100	0.42	0.95	25

Experimental Photo Elasticity Technique

The distribution of stresses along the knee joint replacement part was determined by the use of the 2-dimensional photo-elastic method. The knee's model material was fabricated from a transparent polycarbonate material which was standardized to find the materials fringe constant. The distribution of stresses on the knee modal was estimated according to band order and band factor that resulted from the photo-elastic contours. Lastly the stresses that were obtained from the photo-elastic method was compared with the results that were obtained numerically from ANSYS Workbench (V.16).

The steps taken to construct a model for photo-elasticity,

- Knee Geometry, a 2D photo-elastic model was fabricated, the external contour together with its dimensions traced from a CT scan computer program which has the capability of exhibiting the actual dimensions of the part, as shown in Figure. (4).

Figure 4: CT Scan Image of the Real Dimension for the Artificial Knee Replacement of the Patient

- Preparation of models, the models were fabricated from a photo-elastic material with the aid of a computer numerical control (CNC). This feat was accomplished by firstly creating a 2-dimensional model using an AutoCAD (V.2015) software. In order for the photo-elastic model to have minimum residual stresses the models were cut with a cold water jet low cutting speed with a small feed rate. Thus we obtained a smooth edged modal with very little residual stresses.

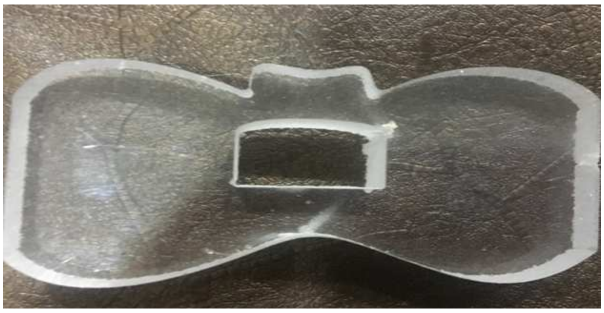


Figure 5: Stem Photo-Elastic 2D Model

- Equipment, Figure (6). illustrates the EFO gear used for the experimental part and conducts the feasible part-elasticity theory of this research in addition to the strength of materials and structure theories.

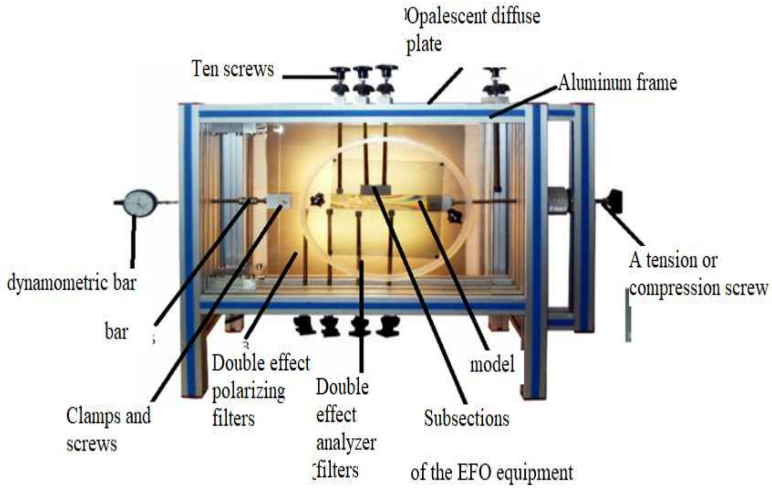


Figure 6: General View of the EFO Equipment

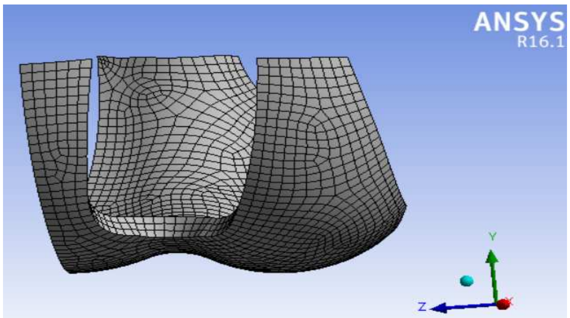
- Ground reaction force (GRF) Measurement, a treadmill force plate is to be used to obtain the ground reaction force to find the forces that are affecting the knee joint. The experiment was replicated three times under different boundary conditions, and these were: without damping, with silicon damping and sneakers with ground air which is illustrated in Figure 7 with a speed of 0.5 Km/h. the results were submitted to a computer via a USB. From these results the maximum effecting force was calculated, as illustrated in Figure., 8 using

Figure 7: Damping Shoe

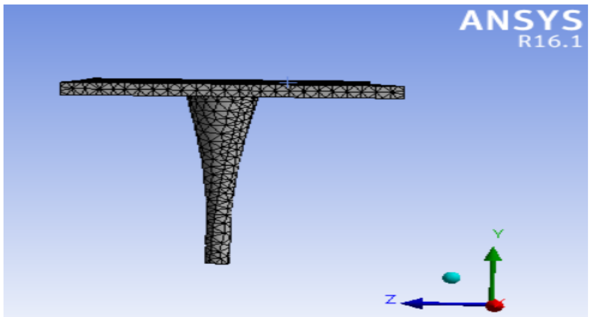
Figure 8: Ground Reaction Force Test

Numerical Work

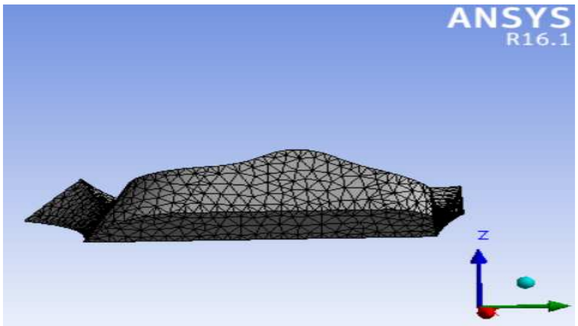
For calculating stresses with dissimilar loading settings during dissimilar damping and the knee's replacement's finite analysis was discussed in detail. It is vital that the stresses on the replaced knee be evaluated in a study or investigation. Here the finite element method is ideal for this, [34-42]. The methods 1st phase is to choose which kind of analysis in ANSAYS Workbench (V.16). Phase two is to form a three dimensional model for the femora, tibia part and the articulating surface. There was a problem of entering the replacement's part contour into ANSYS, so a stem was installed into the patient's body. The images were taken from a CT scan (computed tomography), then an optimum mesh is chosen for the used modal [43–48], Figure 9 illustrates the meshed components of the joint to be replaced, while Figure. 10 shows the boundary conditions used to solve the mechanical modal. The procedures third phase was to send the dimensional model that was created by SOLID WORK (V.2015), of the stem, via an extension (sat) to the ANSYS's WORK BENCH (V.16). The fourth and final phase was to allocate the model's material properties in addition to others and they are the application of loading forces, applying the boundary conditions applying the loading forces which estimated from GRF test and equation of motion (3, 4, 5 & 6). In which the Material's mechanical properties can be assessed experimentally. Therefore the assessed numerical results are dependent and acceptable to be compared with results obtained from the experimental part [49-52].



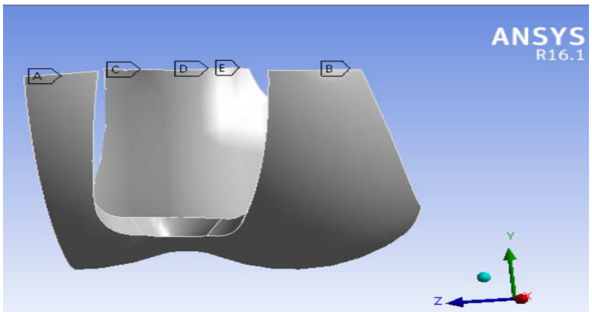
(a) Femoral Component



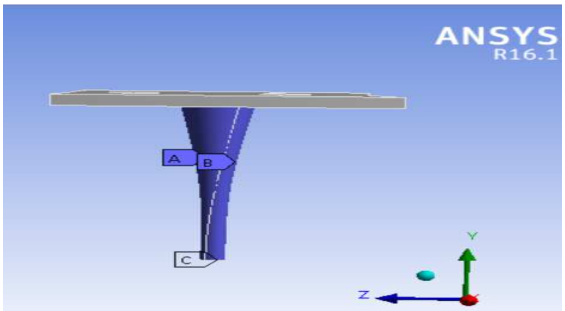
(b) Tibial Component



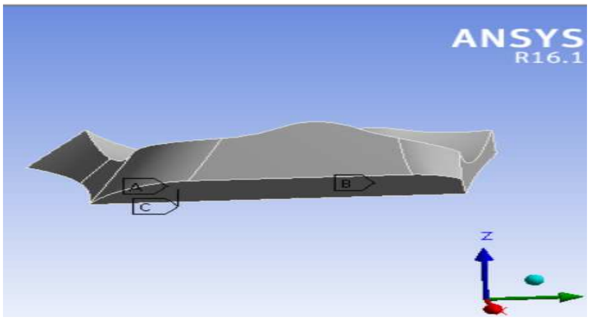
(c) Articulating Surface Component
Figure 9: Total Knee Replacement Component Mesh



(a) Femoral Component



(b) Tibial Component

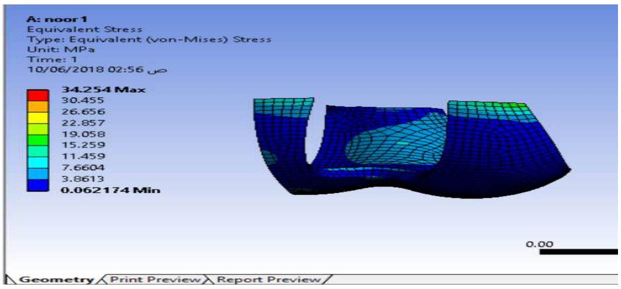


(c) Articulating Surface Component
Figure 10: Fixed Boundary Condition of Total Knee Replacement Component

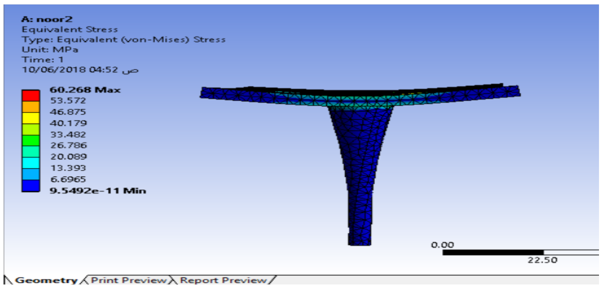
RESULTS AND DISCUSSIONS

The distribution of stresses for each sneakers illustrated in figures. 11, 12 & 13. This was accomplished with the aid of the photo-elastic and numerical methods for each sneaker. The value of these stresses presented in tables 3, 4 and 5) for femoral, tibial and the articulating surface component.

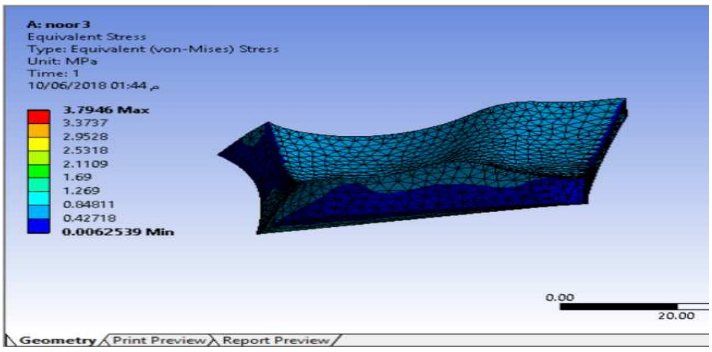
Also the stress either increases or decreases depending on the sneaker and the damping that is used according to the results that were obtained, it showed that all the cases were safe and within the factor of safety limits for prosthetic knee.



(a) Femoral Component

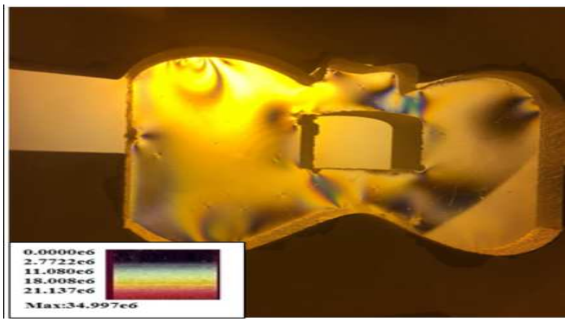


(b) Tibial Component

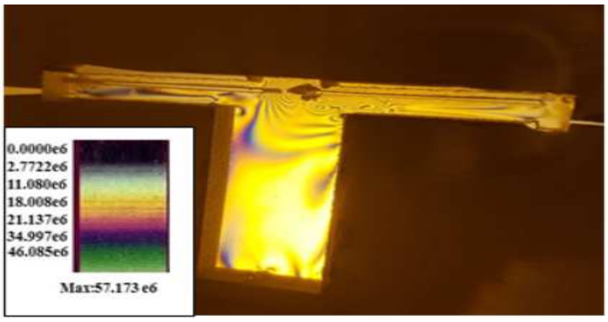


(c) Articulating Surface Component

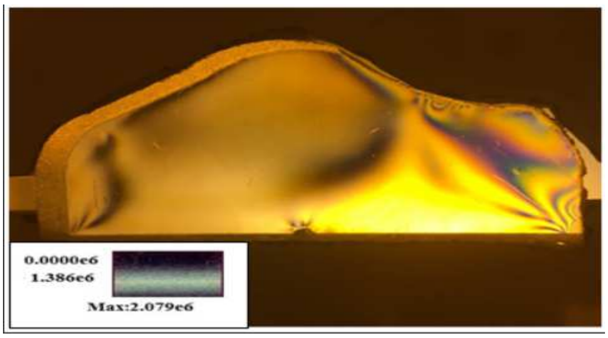
Fi. 11. I. Ansys Analysis



(a) Femoral Component



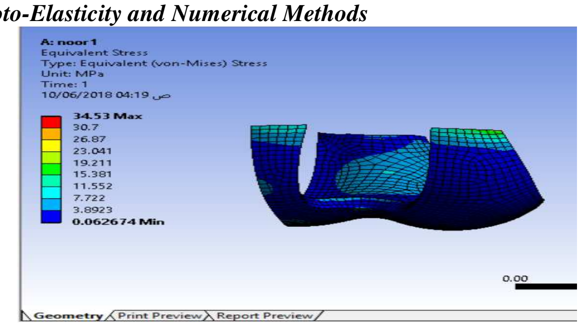
(b) Tibial Component

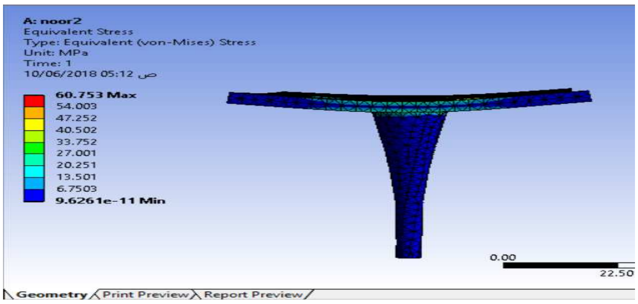


(c) Articulating Surface Component

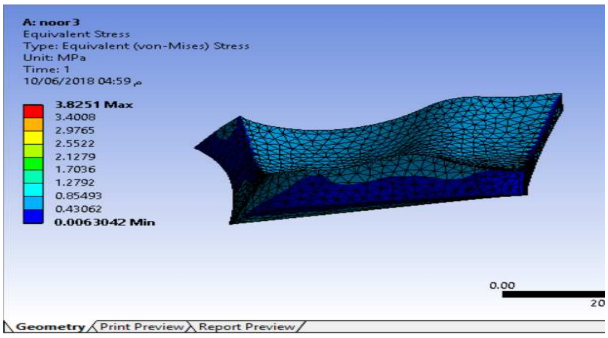
Figure 11: II. Photo Elasticity

Figure 11: Distribution Stress without Damping

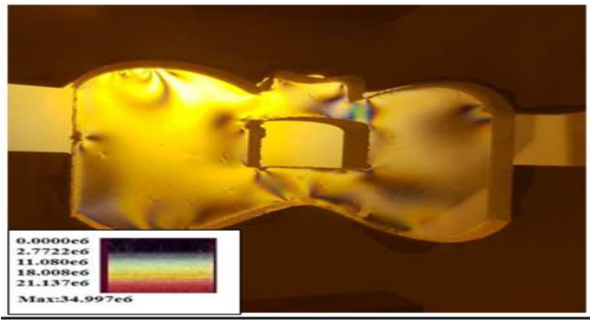


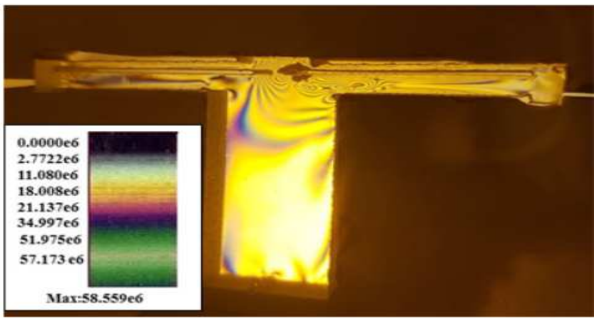


(a) Femoral Component **(b) Tibial Component**

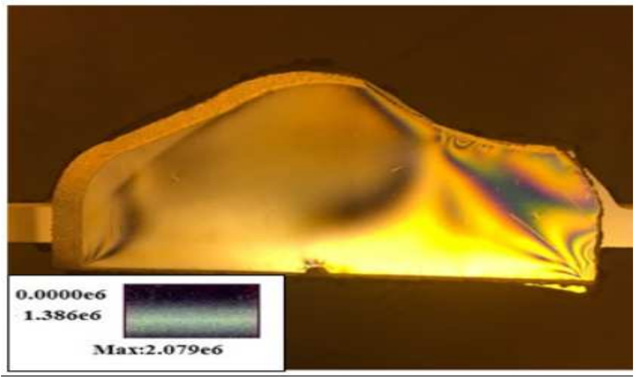


(c) Articulating Surface Component
Fi. 12. I. Ansys Analysis

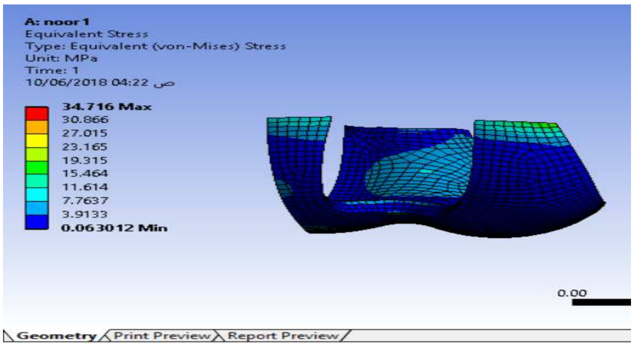




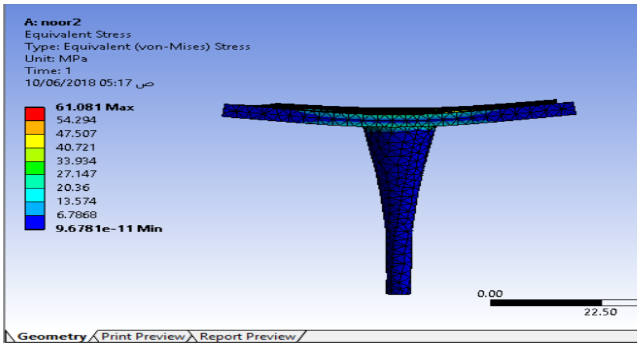
(a) Femoral Component **(b) Tibial Component**



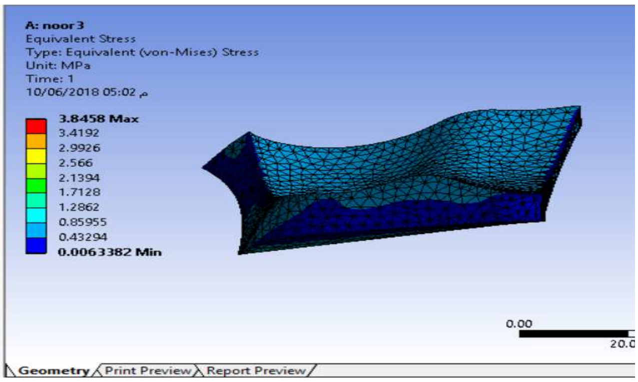
(c) Articulating Surface Component
Figure 12: II. Photo Elasticity
Figure 12: Distribution Stress Athletic Shoes with Ground Air Damping



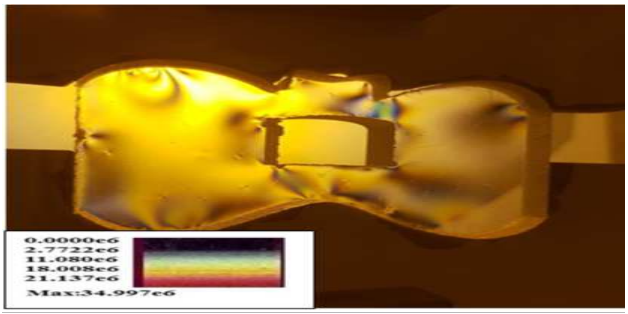
(a) Femoral Component



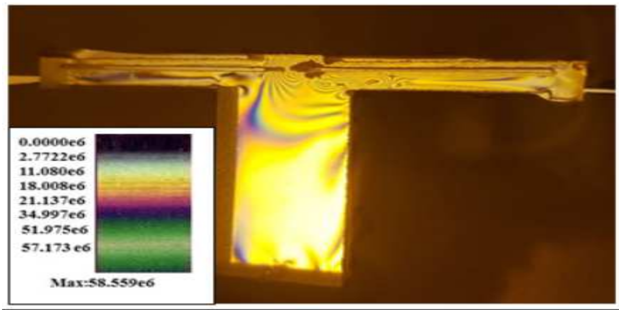
(b) Tibial Component



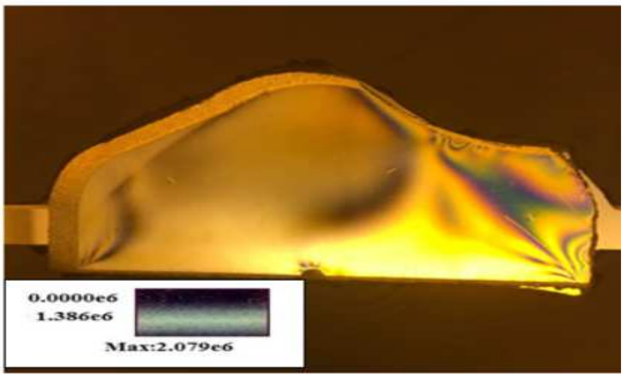
(c) Articulating Surface Component
Fi. 13. I. Ansys Analysis



(a) Femoral Component



(b) Tibial Component



(c) Articulating Surface Component
Figure 13: II. Photo Elasticity
Figure 13: Distribution Stress Athletic Shoes with Ground Air with Silicon Damping

Table 3: Comparison of Stress Distribution between ANSYS and Photo Elasticity for Femoral Component

Type of Damping	Distribution Stress (MPa)		S.F. of ANSYS	S.F. of Photo Elasticity
	ANSYS	Photo Elasticity		
Athletic shoe with ground air	34.53	34.99	30.98	30.58
Athletic shoe ground air with Silicon damping	34.71	34.99	30.82	30.58
Without damping	34.25	34.99	31.24	30.58

Table 4: Comparison of Stress Distribution between ANSYS and Photo Elasticity for Tibia Component

Type of Damping	Distribution Stress (MPa)		S.F. of ANSYS	S.F. of Photo Elasticity
	ANSYS	Photo Elasticity		
Athletic shoe with ground air	60.75	58.55	17.61	18.27
Athletic shoe ground air with Silicon damping	61.08	58.55	17.51	18.27
Without damping	60.26	57.17	17.75	18.71

Table 5: Comparison of Stress Distribution between ANSYS and Photo Elasticity for Polyethylene Articulating Surface

Type of Damping	Distribution Stress (MPa)		S.F. of ANSYS	S.F. of Photo Elasticity
	ANSYS	Photo Elasticity		
Athletic shoe with ground air	3.82	2.07	8.63	15.94
Athletic shoe ground airwith Silicon damping	3.84	2.07	8.59	15.94
Without damping	3.79	2.07	8.7	15.94

CONCLUSIONS

- The results for both (photo-elastic & numerical) methods indicated that damped shoes are safe.
- According to the stress distribution results using ANSYS work bench program (V.16), the maximum values of stress at the femoral component, tibia component and articulating surface component for the case without damping were (34.25, 60.26, 3.79) Mpa respectively. While when using the athletic shoe with ground air the values of stresses becomes(34.53, 60.75, 3.82) Mpa respectively. Finally using ground air sneakers with silicon damping the values of stresses become (34.71, 61.08, 3.84) MPa, respectively.
- According to the stress distribution results using photo-elasticity method, the maximum values of stress at the femoral component, tibia component and articulating surface component for the case without damping were (34.99, 57.17, 2.07) Mpa respectively. While when using the athletic shoe with ground air the values of stresses become (34.99, 58.55, 2.07) Mpa respectively. Finally using ground air sneakers with silicon damping the values of stresses becomes (34.99. 58.55, 2.07) MPa, respectively.
- The safety factor results shows that best case is when using ground air sneaker with silicon damping shows during the values of safety factor for femoral component, tibial component and articulating surface component were (30.82, 17.51, 8.59) respectively for ANSYS work bench program (V.16).

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